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White Paper

Societal Challenge:

Arrayed Microchannel Manufacturing:

Enabling a New Efficiency Paradigm in the Chemical and Energy Industries

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Introduction

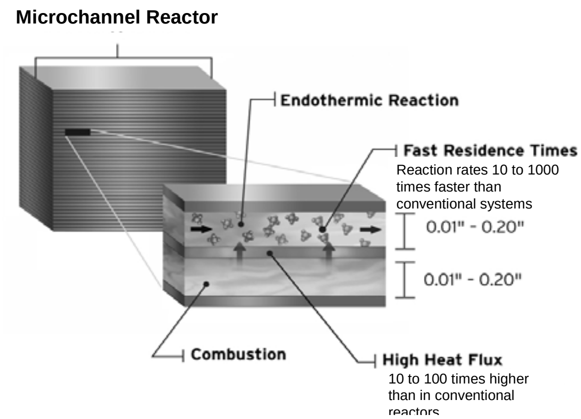
Multiple for-profit and non-profit organizations in the U.S. and around the world are developing microchannel process technology applications, which hold the potential to significantly reduce the capital investment costs and improve efficiency of a wide range of commercially important processes in the energy and chemicals industries. Microchannel process technology, or simply microchannel technology, has been proven to be advantageous at laboratory and pilot scales, and is now being scaled-up to produce commercially significant quantities of chemicals and energy products. This white paper makes the case for a significant public sector investment to develop low cost, high precision manufacturing techniques that will speed the deployment of microchannel technology in applications ranging from hydrogen generation to biofuel production to chemical synthesis.

Research and development efforts for microchannel manufacturing:

- Address an ***area of critical national need*** – dependence on foreign energy resources due to insufficient domestic fuel production and inefficient use of energy in the chemical industry. In total, low cost manufacturing of microchannel enabled processes could lead to the production of 4.6 million barrels per day of domestic biofuels, and substantially reduce the energy consumption of U.S. chemical industry. The net result would be energy savings equivalent to over 4.8 million bpd, more than current oil imports.
- Produce a ***transformational result*** – a set of manufacturing techniques that will permit the fabrication of low cost microchannel devices that can dramatically improve the economics and efficiency of a range of unit operations, including reactors, heat exchangers, distillation, mixing and separations.[1] Furthermore, microchannel technology is an enabling technology for the production of nanomaterials.
- Overcome a ***societal challenge*** – failure to update industrial processes with more efficient alternatives, including microchannel based facilities, has a number of consequences, including continued dependence on foreign energy resources, unnecessary emissions of greenhouse gases and a less competitive domestic chemical industry.

Background

Systems based on microchannel technology have the potential to transform the energy and chemical processing industries by greatly reducing the size of chemical reactor hardware. This technology has many parallels with the microelectronics that revolutionized the computer industry because it can dramatically reduce the size of reaction processing hardware while improving performance. Chemical reactor units based on microchannel technology are characterized by parallel arrays of microchannels, with typical dimensions in the 0.1 to 5.0 mm range. Processes are accelerated 10 to 1,000 fold by reducing heat and mass transfer distances, thus decreasing transfer resistance between process fluids and channel walls. Reactor volumes can be reduced 10-fold or more compared with conventional reaction unit hardware. These smaller reactors significantly reduce the cost of processing equipment, limit by-product formation and improve system efficiency.[2]



	units	Velocys	Conv.
Heat Transfer			
Convective	W/cm²	>50	<10
Boiling	W/cm²	>250	<50
Reaction Times			
Gas Phase	sec	0.001-0.1	1-10

Figure 1. Microchannel Technology Intensifies by Improving Heat and Mass Transfer

Microchannel technology increases the efficiency, effectiveness and profitability of chemical and energy industries. As one example, microchannel technology enables thin film, heat integrated distillation, which can reduce the height of distillation equipment by a factor of 50 and reduce the energy required for separation by more than 50% compared to traditional distillation columns.[3]

At Velocys Inc. of Plain City, Ohio, Georgia Tech, Oregon State University and elsewhere around the world, microchannel devices have demonstrated the ability to intensify chemical reactions. However, to fulfill their commercial potential, microchannel devices must be cost effectively manufactured at larger scales. The challenges associated with this are rooted in the manner in which microchannel devices are scaled up by “numbering up” to form microchannel arrays. Numbering up means that capacity is increased simply by adding (i.e. arraying) parallel microchannels. The proposed development program will solve the problem of cost effectively manufacturing microchannel arrays and reactors by developing a suite of low cost, high precision manufacturing techniques.

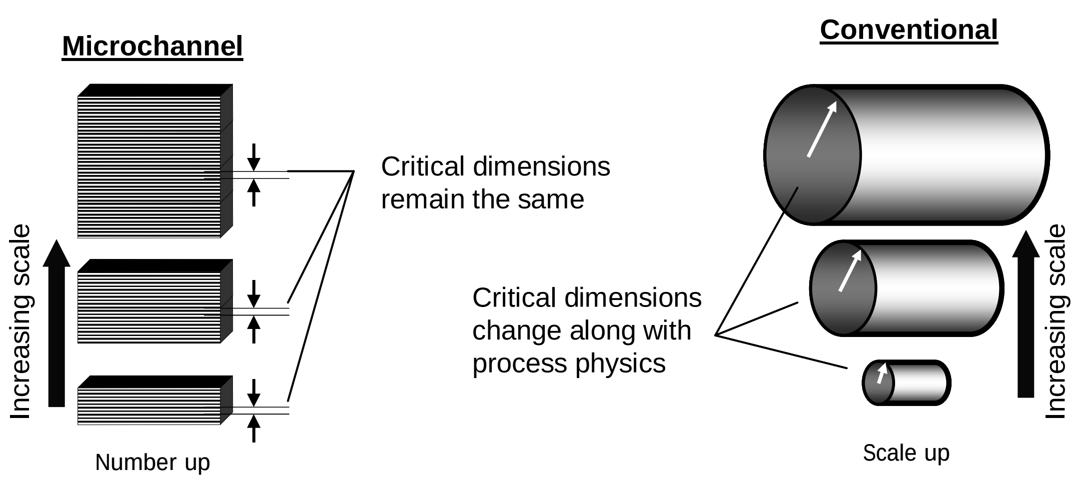


Figure 2. Critical Parameters Stay Constant in Microchannel Numbering-up

Microchannel Applications

Microchannel technology is a versatile platform that can dramatically improve a range of applications. The table below summarizes the on-going and past development programs at Velocys. This is far from an exhaustive list since many other entities are also pursuing microchannel solutions, including Georgia Tech, Oregon State, Chart, Pacific Northwest National Laboratory, Stevens Institute, FMC, Delphi, Institut für Mikrotechnik Mainz (Germany), BASF, Clariant, Compact GTL (UK), and many others.[4]

Table 1 – Microchannel Applications and Associated Benefits and Technology Status

Application	Benefits	Status
Biofuels (Fischer-Tropsch)	Enable cost effective production of biofuels	Small commercial demonstration, second demo to start in mid-2011
Hydrogen (steam methane reforming)	Improved energy efficiency, small footprint enables offshore installation	Large lab-scale experiments validated benefits
Ethylene (oxidative dyhydrogenation)	Enables novel pathway and 20+% energy	Lab-scale experiments validated benefits
Vinyl Acetate Monomer and others (selective oxidation)	Improved selectivity and reduced energy consumption	Lab-scale experiments validated benefits
CO_2 concentrator and other separations (thermal swing absorption)	Improved separations with reduced energy losses	Components operated separately
Ocean Thermal Energy Conversion and others (Heat Exchangers)	Reduced size and pressure drop lower cost of overall system	Modeling results indicate significant improvements
Hydroprocessing biofuels and heavy hydrocarbons	Improved selectivity, reduced need for excess hydrogen	Lab-scale experiments validated benefits
C2 splitter and others (distillation)	Far shorter height permits more stages, improved separation	Lab-scale experiments validated benefits
Personal care and others (emulsions)	Highly stable emulsions without over-sheering	Demonstrated in a commercial setting

Arrayed Microchannel Manufacturing

As shown in Figure 2, the numbering up method of increasing scale reduces risk by keeping the reaction physics and channel flow hydrodynamics the same. This is contrasted with the scale-up of conventional process technologies where the reaction physics and hydrodynamics change at each scale. However, the numbering up approach introduces its own challenges as each of the thousands of microchannels in a reactor must be sufficiently uniform to ensure even flow distribution and reactor performance.

Depending on the material employed, many microchannel fabrication techniques can be used to create small, uniform passages. However, most large-scale applications require the use of ferrous aloys or similar materials. One methodology that is being pursued for commercial-scale microchannel reactors is known as microchannel lamination, or microlamination. This technique is thought to provide cost effectiveness, design flexibility to accommodate a complex suite of chemical unit operations in a single component, and the tolerances required to make sufficiently uniform internal passages. Microlamination involves producing many parallel microchannels by interleaving (stacking) and consolidating (bonding) thin sheets of material (laminae or shims) with microchannel patterns. The steps in microlamination are shown in Figure 3 below.

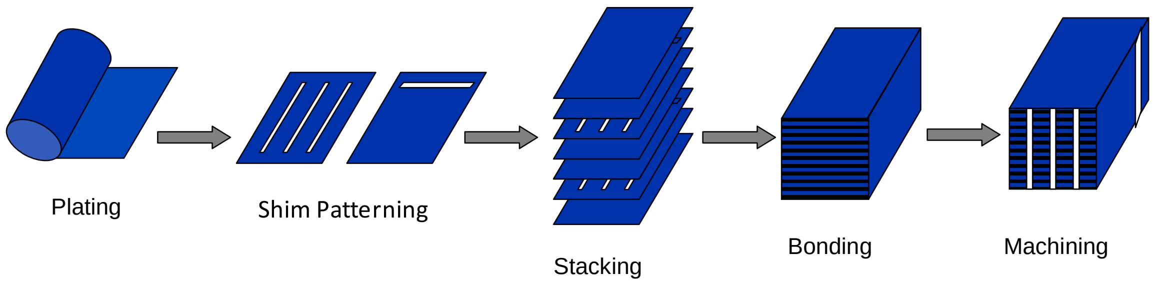


Figure 3. Laminate Construction Technique to Produce Microchannel Reactors

The dominant approach to microlamination currently involves electroplating, photochemical etching (PCE) and diffusion brazing. These techniques have enabled initial markets but significant cost reductions are required to meet future cost targets leading to wider impact of microchannel technology. Alternatives for shim patterning include stamping and laser cutting. The cost of these varies greatly as does the tolerances achievable with each technique. Depending on the pressure, temperature and service, bonding can be achieved through brazing or more intensive processes. Costs for machining and attaching of headers can also be reduced depending on the bonding technique employed and other application-specific attributes. Development efforts are required to select the preferred techniques and validate their ability to meet the required tolerances for commercial-scale microchannel devices.

In addition to advancing more economical techniques, other areas for microchannel manufacturing development include:

1. Integrating membranes and other heterogeneous laminae, such as highly conductive barriers.
2. Application of protective coatings to minimize corrosion and coking
3. Novel approaches to catalyst integration and refurbishment
4. Integration of fluidic sensors and actuators
5. Failure mode diagnosis of manufacturing yield issues
6. Development of manufacturability design tools
7. Development of new process machine tools including novel forming, deposition and furnace equipment
8. Techniques to form more complex passages – beyond rectangular and circular
9. Integration of microchannel components with plants and piping

A more complete list of microchannel manufacturing development needs are included in the "Proposed Development Program" section below.

<u>Technology Innovation Program (TIP) Criteria</u>

A. Maps to Administration Guidance

The two primary market applications for microchannel technology both enjoy strong support from the Obama administration. As evidenced by the June 29, 2009 DOE press release pasted below, the current administration has made consumer and industrial energy efficiency a top priority. President Obama has also clearly stated continuing support for advanced biofuel production, as shown in the excerpts of a May 5, 2009 White House press release announcing a biofuels working group.

U.S Department of Energy, June 29, 2009

Obama Administration Launches New Energy Efficiency Efforts

Will save billions for consumers, business while helping to create new jobs and strengthen American competitiveness

WASHINGTON - Building on the action by the U.S. House of Representatives in passing historic legislation that will pave the way for the transition to a clean energy economy, President Barack Obama and U.S. Energy Secretary Steven Chu today announced aggressive actions to promote energy efficiency and save American consumers billions of dollars per year. Today's announcement underscores how the clean energy revolution not only makes environmental sense, but it also makes economic sense - creating jobs and saving money.

"One of the fastest, easiest, and cheapest ways to make our economy stronger and cleaner is to make our economy more energy efficient," said President Obama. "That's why we made energy efficiency investments a focal point of the Recovery Act. And that's why today's announcements are so important. By bringing more energy efficient technologies to American homes and businesses, we won't just significantly reduce our energy demand; we'll put more money back in the pockets of hardworking Americans."

"When it comes to saving money and growing our economy, energy efficiency isn't just low hanging fruit; it's fruit lying on the ground," said Secretary Chu. "The most prosperous, competitive economies of the 21st century will be those that use energy efficiently. It's time for America to lead the way."

The White House, May 5, 2009

President Obama Announces Steps to Support Sustainable Energy Options, Departments of Agriculture and Energy, Environmental Protection Agency to Lead Efforts

Announcement Includes Biofuels Interagency Working Group, Recovery Act Funds for Biofuels Research and Commercialization, and Notice of Proposed Rulemaking on the Renewable Fuel Standard

WASHINGTON – President Obama today announced steps to further his Administration’s commitment to advance biofuels research and commercialization. Specifically, he signed a Presidential Directive establishing a Biofuels Interagency Working Group, announced additional Recovery Act funds for renewable fuel projects, and also announced his Administration's notice of a Proposed Rulemaking on the Renewable Fuel Standard.

"We must invest in a clean energy economy that will lead to new jobs, new businesses and reduce our dependence on foreign oil," said President Obama. "The steps I am announcing today help bring us closer to that goal. If we are to be a leader in the 21st century global economy, then we must lead the world in clean energy technology. Through American ingenuity and determination, we can and will succeed."

> [portion of press release removed for brevity] "As we work towards energy independence, using more homegrown biofuels reduces our vulnerability to oil price spikes that everyone feels at the pump," EPA Administrator Lisa P. Jackson said. "Energy independence also puts billions of dollars back into our economy, creates green jobs, and protects the planet from climate change in the bargain."

B. Justification for Government Attention

The broad applicability and energy benefits of microchannel technology provide the justification for public sector investment in this technology platform. The subsections below describe the potential energy, environmental and economic savings associated with broad implementation of microchannel technology.

Reduction of Energy Imports

By enabling biofuels production and improving industrial energy efficiency, the proposed microchannel manufacturing development program can lead to a significant reduction of energy imports from foreign sources. According to the USDA and DOE, the U.S. annual produces 1.3 billion tons of biomass available for energy conversion. In an efficient, microchannel based process this could result in 1.7 billion barrels of high quality, infrastructure compatible biofuels, or 4.6 million barrels per day – substantially more than our current imports from Middle East and Venezuela combined.

Microchannel technology can also reduce energy imports by enabling process energy efficiency According to figures published by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy[5], in 2002, the U.S. chemical and refining industries consumed 8,499 trillion BTUs of primary energy. Of this total, only 4,342 TBTUs are used productively, while the other half of the energy is lost due to inefficiencies. This wasted energy, equivalent to nearly 2 million barrels per day of oil, represents a great opportunity for the chemical industry and the nation at large. Losses attributed to energy conversion (654 for chemicals and 478 for refining) are the ones primarily addressed by microchannel technology. If these could be halved, the savings would be equivalent to over 250,000 barrels per day.

Environmental Impacts

Use of ultra-clean biofuels, such as those produced in a microchannel Fischer-Tropsch (FT) facility, and improving industrial efficiency positively impact the emissions of greenhouse gases (GHG) and other pollutants. Multiple studies have indicated that biofuels produced in an FT process produce 90% fewer life cycle GHG emissions than petroleum fuels. Combusting these fuels also produces less criteria air pollutants as shown in Table 2 below.

Additional GHG and other pollutant reductions stem from industrial efficiency. The primary energy resources used to provide process heating are natural gas and liquid petroleum gas, commonly known as LPG. Combustion of these fuels leads to emissions of both criteria air pollutants and greenhouse gases. Using the assumption that two-thirds the process heating energy is provided by natural gas and one-third by LPG, saving 566 TBTU per year (50% of 1,132 TBTU) would result in emission reductions shown in Table 2. The total reduction in GHG emissions possible equals nearly 4% of total U.S. greenhouse gas emissions.

Table 2. Potential Emission Reduction

	Units	Biofuels Diesel	Process Efficiency Natural Gas[6]	LPG[7]	Total
Resource Reduction					
Energy	TBTU/yr	9,940	377	189	10.500
Volume	per yr	1.7 Bbbl	377 BSCF	2.11 Bgal	
Emission Reduction					
CO	ton	123,000[a]	16,200	8,900	148,100
NOx	ton	0[b]	19,200-53,900	15,900	35,100-69,800
SOx	ton	82[c]	115	95	292
GHG[d]	kton	179,000	23,100	15,100	217,200

Notes: a. Cleaner burning FT fuel expected to produce CO emissions approximately 50% less than petroleum diesel
b. NOx emissions result from engine operating condition, fuel change impact is expected to be negligible.
c. Synthetic fuels are sulfur free, calculations assumes biofuels replace Ultra-Low Sulfur Diesel (15 ppm)
d. Greenhouse gas emissions include CO_2 (GWP: 1) and CH_4 (GWP: 21).

Economic Impact

The largest economic impact is the replacement of imported oil with domestically produced biofuels. At the current price of crude oil hovering between $70 to $75 per barrel, 1.7 billion barrels of biofuels equates to about $120 billion fewer imports, or approximately four month's worth of the U.S. trade imbalance. The efficiencies stated above add to the impressive potential energy and cost savings. At the point of full industrial implementation and assuming $8/MBTU, reducing natural gas consumption by 429 billion standard cubic feet per year would result in annual savings of $3.4 billion. The reduction of 2.35 billion gallons of LPG would increase the savings by $1.3 billion.

As stated above, research into microchannel technology is occurring in various areas around the world, including Japan, UK and Germany. Substantial investment in this technology would allow the U.S. to take a leadership position in this emerging field, and it would improve the competitiveness of the domestic chemical industry. For years, chemical production has been shifting from regions that have higher feedstock costs to those with lower cost, including China and the Middle East. Successful development microchannel enabled processes could reverse this trend and bring chemical production and high wage jobs back to the U.S. Furthermore, biofuels and closely related gas-to-liquids (GTL) could create a new industry that would have opportunities both domestically and for export.

C. Essentials for TIP Funding

Other agencies have invested in microchannel process technology applications, but manufacturing remains a key hurdle to implementation. The tables below shows government and private sector support for application based projects proposed by Velocys, but not for manufacturing development.

Table 3. Past Velocys public sector awards for microchannel technology

Subject	Agency	Funding Awarded	Notes
Gas Purification	DOE – National Energy Technology Laboratory	$800K	Operational advantage shown, but cost not competitive
Ethylene	DOE – Industrial Technology Program	$2.2 million	Positive results
Distillation	DOE – Industrial Technology Program	$2.9 million	Performance advantage shown, but cost not competitive
Fischer-Tropsch	DOD – U.S. Army's National Automotive Center	$3.8 million	Completed and moving to demonstration scale
Hydrogen Generation	Ohio Dept. of Development – Fuel Cell Program	$1.9 million	Operational advantage shown, but cost not competitive
Hydroprocessing	Ohio Dept. of Development – Research Commercialization	$5 million	Demonstrated upgrading of FT wax and heavy oils
Hydroprocessing	USDA/DOE Biomass Program	$2.4 million	Work underway for upgrading pyrolysis oil
Manufacturing	Ohio Dept. of Development – Research Commercialization	$0	Not funded
Manufacturing	DOE – National Energy Technology Laboratory	$0	Not funded

Proposed Development Program

Although processes for making microchannel arrays are currently available, each step in the manufacturing process could be improved to lower the cost of fabrication and improve the quality of microchannel reactors opening up new markets for energy efficiency and renewable energy. The process starts with material sourcing and continues all the way through field deployment, including connecting the microchannel components to commercial scale plant piping. Although, more study is needed to develop a detailed plan, the paragraphs below describe the key challenges associated with microchannel manufacturing. The anticipated cost of a program to address these challenges is between $15 million and $25 million, and is expected to last 4 to 6 years.

Material sourcing – Microlamination requires stacking hundreds of shims on top of one another. This means that small variations in thickness can result in lopsided reactors. Development is needed to better manage crowning from mills. Other material sourcing issues include grain size, uniformity of composition and surface conditions, all of which can significantly impact downstream patterning and bonding. Further development efforts could also look into new alloys specifically for microchannel devices; ones that facilitate stacking and joining, and permit high temperature operations.

Preparation for joining – Most joining methods require some type of filler material or surface preparation. Like the base material, the requirements for plating, dispensing, screen printing and other forms of surface preparation include a high level of uniformity, which is often difficult to achieve at the accuracies required with existing processes.

Lamina patterning – Several approaches have been tried to shape the shims that make up a microchannel device including stamping, photo-chemical machining (PCM), and laser cutting. Different approaches have different challenges including burr formation, residual stress and high cost. Also included in this category are additive techniques , which show great promise but are at an early stage of development.

Integration of heterogeneous laminae – Many separations devices require the integration of membranes and other heterogeneous structures within the stack of laminae. New methods for integrating heterogeneous laminae are required.

Joining – The next step is consolidating the stack of shims into a solid microreactor. Possible approaches here include welding, adhesives, brazing, and diffusion bonding. The challenge with each is achieving uniform properties without altering the dimensions of the internal channels. For high temperature and high pressure applications, the current preferred process is diffusion bonding, which has been shown effective for sealing reactors, but not necessarily always resulting in the desired material properties. However, this requires very long heat-up and cool-down cycles, which necessitate long residence times in bonding furnaces and result in excessive costs. New production techniques for reducing ramp rates and capital equipment costs associated with diffusion bonding and brazing include internal convective heating and differential thermal expansion clamps. Potential new approaches for joining low-temperature microchannel arrays include thermal adhesives.

Corrosion protection & passivation – Microreactors speed up chemical reactions. This acceleration typically favors desired products over by-products, but can at times increase the rate of corrosion and promote side reaction. Surface treatments, including passivation via aluminization, have proven effective at controlling corrosion and quelling side reactions, such as coking. However, the complexity of the internal passages of a microchannel device presents a challenge for complete and uniform application of coatings. Many other surface treatments are needed to control the chemical and thermal conditions of surfaces. All of these surfaces are susceptible to high-temperature packaging techniques that can change surface properties. New techniques for packaging these surfaces are needed.

Catalyst application – Many catalyst forms, including packed beds, engineered supports and wash coats, are compatible with microchannel architecture. However, selectively and uniformly applying catalyst inside the reactor, as well as refurbishing and replacing the catalyst presents some unique challenges. Development is needed to improve catalyst integration, extend catalyst life, and improve procedures to refurbish/replace catalyst.

Quality control – Once microchannel reactors are fabricated, protected against corrosion, and charged with catalyst, they need to be inspected before being put into service. Sufficiently uniform flow is required for optimal performance, so it is critical to determine if channels have been blocked or constricted. Efforts are required to develop non-invasive QC procedures to detect joint flaws, blocked channels and other defects. Furthermore, corrective actions need to be developed to salvage usable reactors, such as blocking or unblocking select channels. Perhaps the largest contributor to cost is manufacturing yield. Leakage and warpage defects are typically associated with non-uniform thermal and stress distributions generated during manufacturing. Efforts are needed to study known defect modes in an effort to develop design rules for circumventing yield issues in manufacturing.

Plant integration – Connecting microchannel devices to the "big" pipes in a commercial facility also presents challenges. External manifolds need to be attached by brazing or welding across the joints of the stack. Aggressive joining techniques can adversely affect the mechanical integrity of the microreactor. It is also desirable to have high temperature/high pressure connections that can be assembled and disassembled on an as needed basis.

Other – Other potential areas for development include investigating new materials for industrial scale microreactors, and assessing material properties after fabrication and during operation. High temperature extruded polymers could be used for some applications and these would theoretically be easier to manufacture than metal reactors. Many conventional technology reactor systems utilize corrosion coupons made of the same material to understand material properties during fabrication and operation. Attention is needed to develop a similar mechanism for microchannel components.

Conclusion

This white paper recommends a significant investment in microchannel manufacturing techniques. Low cost, high volume manufacturing techniques will speed the deployment of microchannel process technology. Once developed, these manufacturing techniques can be applied to a wide range of processes, including production of advanced biofuels, hydrogen, ethylene and many more.

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